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Annual Report

# Interferometric Measurement

Grant No: N00014-92-J-1302

P.I.'s: H. A. Haus and E. P. Ippen

Staff: Dr. Shu Namiki, visiting scientist
Dr. Moti Margalit, post-doc
Charles Yu, graduate student

## Goal of Research

The goal of the research is the generation of squeezed radiation for use in interferometric measurements, via the third order Kerr nonlinearity in fibers and employing fiber components. This method of generating squeezed radiation obviates the need for frequency doubling required in parametric processes using the second order nonlinearity.

## Soliton Squeezing

The successful experiments of K. Bergman resulting in shot noise reduction by 5.1 dB were performed with Gaussian pulses at the zero dispersion wavelength (1.3μm) of silica fibers. With no dispersion, every time-interval of the pulse acts independently as a pump and squeezes the vacuum fluctuations within its interval. The squeezed radiation consists of in-phase and quadrature squeezing ellipses that vary across the intensity profile of the pulse. Detection of the squeezed radiation in a balanced detector averages over all time intervals and results in less than optimum shot noise reduction. Solitons in fibers of net negative dispersion squeeze "as a unit", the amplitude and phase fluctuations of the soliton are gaussian distributed with one single squeezing ellipse. Therefore, soliton squeezing is not subject to reduction by averaging within the detection.

Two experiments were carried out with solitons, one at IBM the other at MIT. The greater degree of shot noise reduction of 2.1dB achieved at MIT still fell way below expectation. We believe that the modelocked lasers used in these experiments, coupled cavity soliton lasers as developed by Mollenauer, had excessive amplitude fluctuations that prevented the squeezing. Further, it should be noted that these experiments tried to overcome the effect of Guided Acoustic Wave Brillouin Scattering (GAWBS) by the use of very powerful pulses at a low repetition rate. A better way of overcoming GAWBS is through the use of high pulse repetition rates. Whereas the noise sidebands produced by GAWBS convolve into the measurement bandwidth, this does not occur for pulses at high repetition rates. For this reason we developed a low noise modelocked fiber ring laser at high repetition rate as described in the next section. In the coming funding period we intend to apply the newly developed source to soliton squeezing.

## A High Repetition Rate Soliton Source

To achieve high repetition rate modelocked pulse operation either the cavity of the laser is made as short as possible, or the laser is induced to operate at a repetition rate higher than that dictated by the cavity length.

To achieve low amplitude noise, a laser has to be predominantly modelocked by a passive amplitude modulation action. To achieve high repetition rates the pulses have to be ordered using either electro-optic or optical feedback. We have demonstrated pulse ordering at 1 GHz of a passively mode locked fiber laser. The unique aspect of this work is the usage of phase modulation feedback to order the pulses. This permitted long term stability and low noise operation.

The experimental setup is shown in Fig. 1. The laser had an internal anomalous dispersion of 5 ps/nm/km, and was pumped by 400 mW at 980 nm. The additive pulse mode-locking (APM) action occurred at the polarization sensitive isolator, and the second polarization beam splitter served as a variable output port. The electronic feedback loop consisted of a 2 GHz photodiode, 60 dB of gain, and a RF filter with a 3 MHz bandwidth centered at 1 GHz. The RF signal was fed into a phase modulator with a bandwidth of 1 GHz and a $V_\pi$ voltage of 1.4 Volt. The repetition rate was determined by the RF filter. The appropriate RF phase delay was implemented with a variable microwave adjustable phase delay. Adjustment of the waveplates changed the APM action and induced passive modelocking. Further adjustment led to pulse ordering at 1 GHz. The lasers optical frequency could be tuned by adjusting the 10 nm optical filter. It should be noted that this laser is relatively short compared to previously reported high repetition rate fiber lasers and the basic repetition frequency was ~25 MHz. To achieve a large number of pulses in the cavity, in addition to the amplitude limiting action (APL) of the APM, the optical filter imposes a larger loss on shorter pulses thus limiting the amplitude.

A typical RF spectrum of the laser operating without the phase modulation feedback is shown in Fig. 2. Since the multiple pulses in the cavity have a slightly different center frequency there are multiple collisions, constant relative motion of the pulses, and the RF spectrum changes constantly. In this laser we have not been able to observe the self ordering phenomenon. When the electro optic feedback was applied the RF spectrum stabilized. Because of the feedback the 1 GHz harmonics were amplified, while the basic cavity harmonics were suppressed, as shown in Fig. 3. As opposed to an actively modelocked laser we see no supermode competition, but rather a distinct locking at 1 GHz. A 40 dB sidemode suppression implies an amplitude noise energy at the fundamental cavity repetition rate of approximately 23 dB or 0.5%. Since ~50 pulses are circulating in the cavity this corresponds to zero dropout. Assuming a hyperbolic secant pulse the time bandwidth product was 0.38. In this case the laser emitted 6 mW from the output port. The amplitude noise of the laser was measured around the first harmonic, and is shown in Fig.4. This noise is comparable to previously reported low noise fiber lasers operating at the basic cavity repetition rate, and implies that the feedback mechanism does not increase the amplitude noise.

In soliton transmission schemes both phase and amplitude modulation have been used to reduce timing jitter and synchronize the solitons. However in our system when the phase modulator was replaced with an amplitude modulator, the laser was highly unstable and favored operating in a predominantly actively mode locked regime, with the wide pulses. This instability arises from the competition of the two amplitude modulating mechanisms, namely the electro-optic modulation and the APM action. In the phase modulated laser no such competition exists, and the laser is inherently stable.

## Squeezing without Sagnac Loop

In the preceding reporting period, we proposed a method of squeezing that does not use a Sagnac loop and does not require a high pulse repetition rate[1]. This is accomplished by the use of a short fiber and high intensity pulses. GAWBS is also less harmful in a set-up using high intensity pulses and short fibers. The squeezing occurs via cross-phase modulation between the pump in one polarization and the signal in the orthogonal polarization. The fiber is not polarization maintaining, but must be short (30 cm) to prevent undesired is of the order of 3-10 m. A polarization beam splitter is used to separate the pump and the squeezed vacuum. The experimental set-up is shown in Fig.5.

The source for this form of squeezing is different from the high repetition rate source described above. The design is based on the stretched pulse fiber ring laser developed at MIT and now commercialized by Clark-MXR, Inc. The ring consists of two segments of opposite group velocity dispersions that almost balance, with only small net negative dispersion remaining. The pulse traveling around the ring alternately stretches and compresses, thus greatly reducing the nonlinear effects in the fiber ring, effects that tend to limit the achievable peak pulse intensity in lasers that do not use this principle of operation. The stretched pulse laser can have >2 nJ pulse energy, <100 fs pulsewidth, and the lowest noise levels reported to date. The PBS of the laser will be placed where the pulse is the shortest. One of the fiber pigtails of the PBS will serve as the squeezer. The detection system is the same as in Boivin's paper.

## The Continuum

A soliton traveling along a dispersive fiber is accompanied by noise in the continuum of other excitations possible. If the pulse shape of the local oscillator is chosen properly, the amplitude and phase of the soliton can be detected in a balanced detector arrangement. Different pulse shapes are required for the detection of amplitude and phase. The squeezing soliton pulse has the shape of a secant hyperbolic (denoted henceforth by $f_n(t)$). This pulse shape is appropriate for the detection of the amplitude fluctuations but not for the phase fluctuations, which require a pulse of the shape[2]

$$f_\theta(t) = \left[1-\left(\frac{t}{\tau}\right)\tanh\left(\frac{t}{\tau}\right)\right]\operatorname{sec}h\left(\frac{t}{\tau}\right)$$

Change of the pulse shape via filtering before detection encounters difficulties, since phase coherence must be maintained between the squeezed vacuum and the local

oscillator pulse. We have started an investigation of the sacrifice of squeezing, if we use a secant hyperbolic pulse for the local oscillator, rather than the optimum pulse shape which is a linear combination of $f_n(t)$ and $f_\theta(t)$. For this purpose, we had to develop an expansion theory for the continuum[3].

## References


[1] L. Boivin and H. A. Haus, "$\chi^{(3)}$ squeezed vacuum generation without a Sagnac interferometer," Optics Letters **21**, 146-149, January 1996.

[2] H. A. Haus and Y. Lai, "Quantum theory of soliton squeezing-- a linearized approach," Journal of the Optical Society of America B 7, 386-392, March 1990.

[3] H. A. Haus, W. S. Wong, and F. I. Khatri, "Continuum generation by perturbation of soliton," Journal of the Optical Society of America B **14**, 304-313, February 1997.

## Publications Acknowledging Contract


1. H. A. Haus and F. X. Kärtner, "Optical quantum nondemolition measurements and the Copenhagen interpretation," Physical Review A **53**, 3785-3791, June 1996.
2. S. Namiki, E. P. Ippen, H. A. Haus, and K. Tamura, "Relaxation oscillation behavior in polarization additive pulse mode-locked fiber ring lasers," Applied Physics Letters **69**, 3969-3971, December 1996.
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4. H. A. Haus, W. S. Wong, and F. I. Khatri, "Continuum generation by perturbation of soliton," Journal of the Optical Society of America B **14**, 304-313, February 1997.
5. S. Namiki and H. A. Haus, "Noise of the stretched pulse fiber laser I: Theory," IEEE Journal of Quantum Electronics **33**, May 1997.
6. C. X. Yu, S. Namiki and H. A. Haus, "Noise of the stretched pulse fiber laser II: Experiments," IEEE Journal of Quantum Electronics **33**, May 1997.
7. H. A. Haus and Y. Lai, "Quantum theory of soliton squeezing: a linearized approach," Journal of the Optical Society of America B **7**, 386-392, March 1990.

## Figure Captions

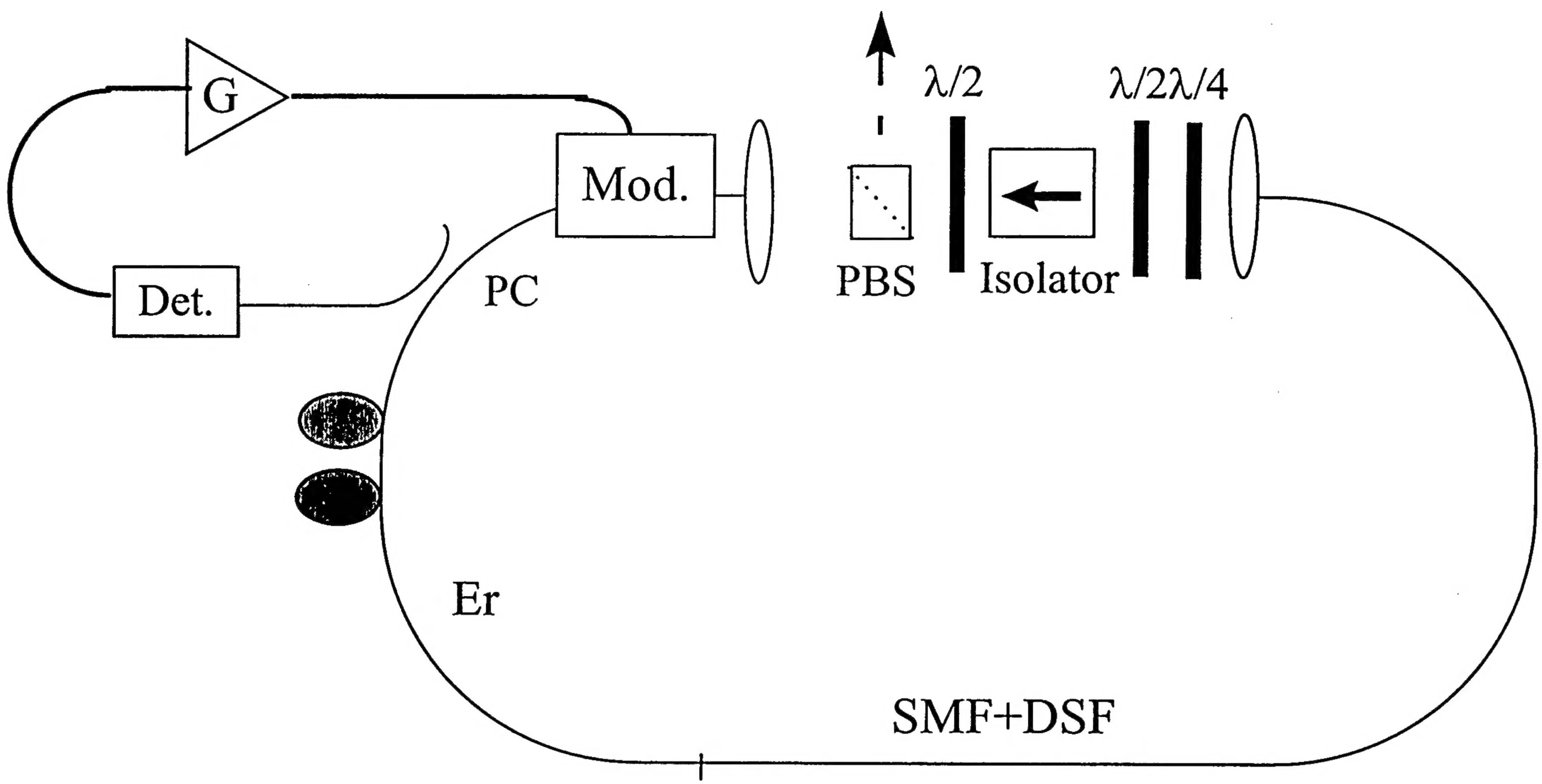
**Figure 1.** Schematic description of the regenerative phase modulated laser.

**Figure 2.** (a) RF spectra of the free running laser. (b) corresponding optical spectrum, FWHM is 5 nm.

**Figure 3.** (a) RF spectra of ordered pulses at 1 GHz. (b) corresponding optical spectrum, FWHW is 5 nm.

**Figure 4.** RF spectrum of amplitude noise around first harmonic (1 GHz).

**Figure 5.** Experimental set-up for squeezing via cross-phase modulation.

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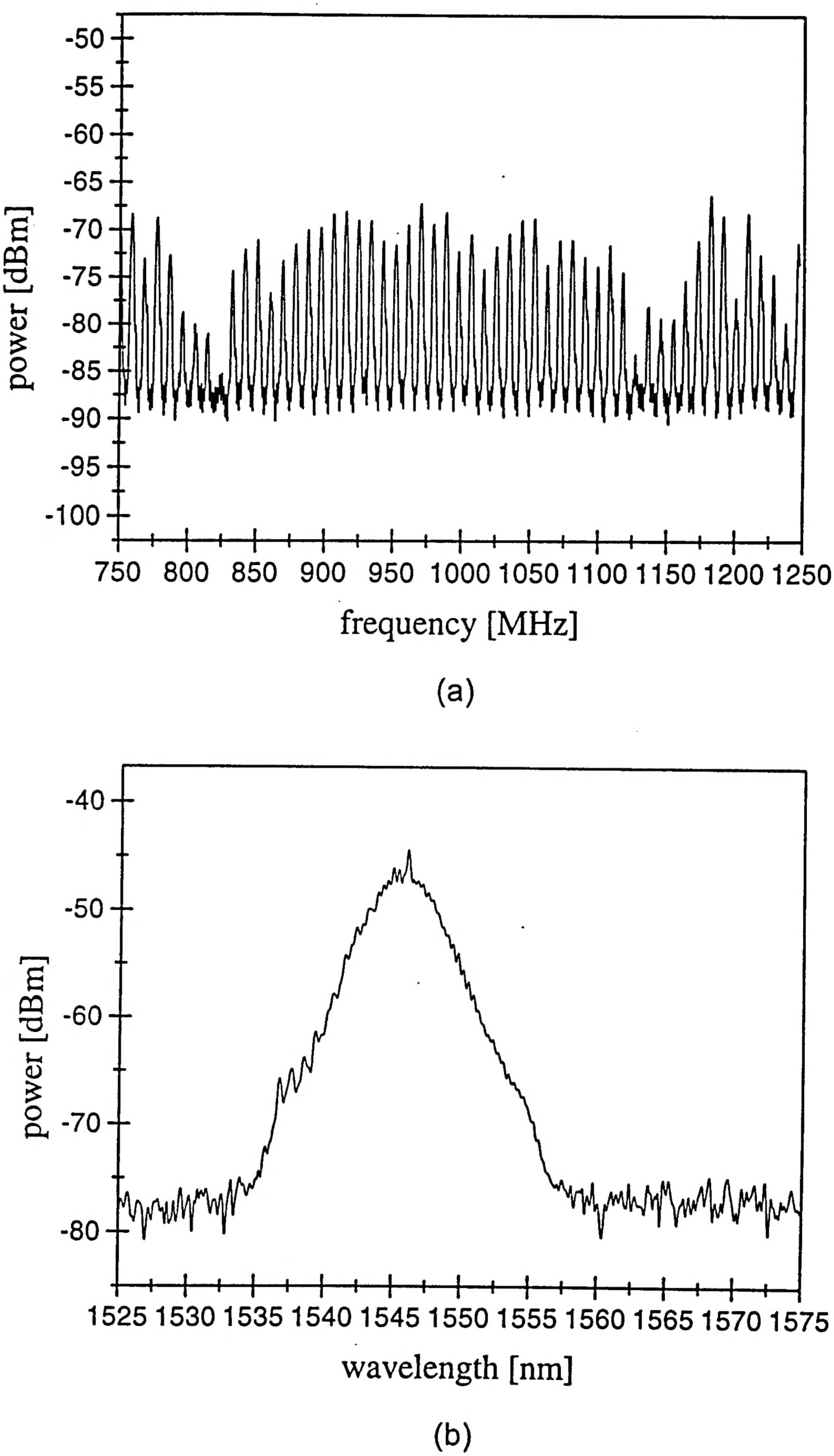
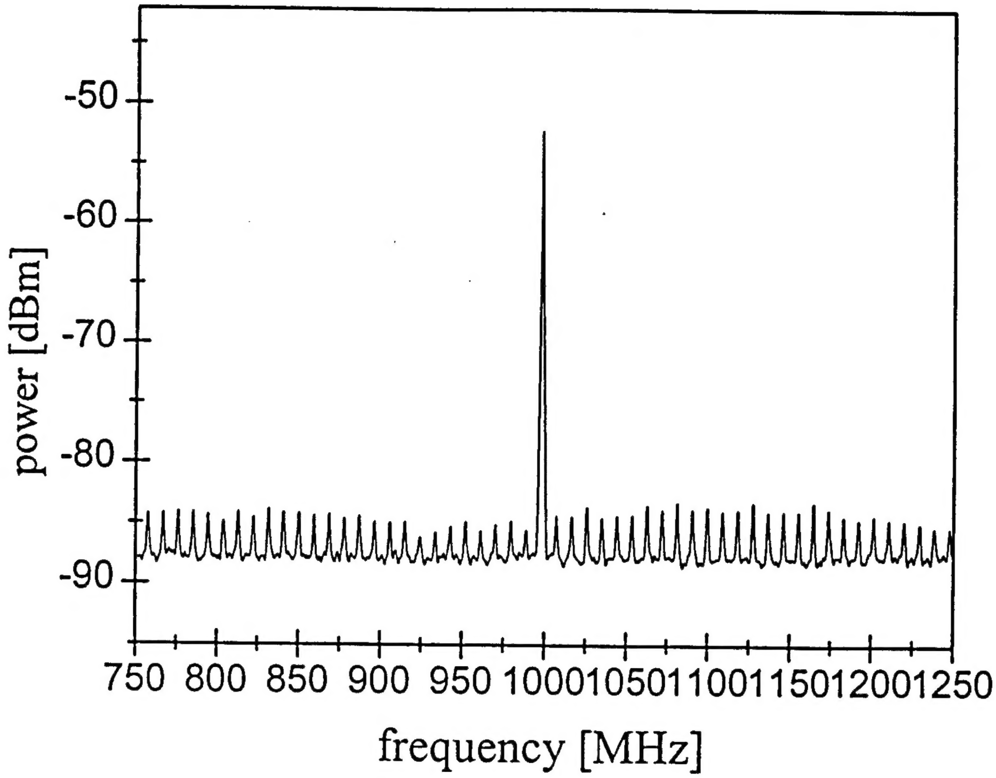

power [dBm]
-50
-55
-60
-65
-70
-75
-80
-85
-90
-95
-100
750 800 850 900 950 1000 1050 1100 1150 1200 1250
frequency [MHz]
(a)
power [dBm]
-40
-50
-60
-70
-80
1525 1530 1535 1540 1545 1550 1555 1560 1565 1570 1575
wavelength [nm]
(b)

Figure 2



-50
-60
-70
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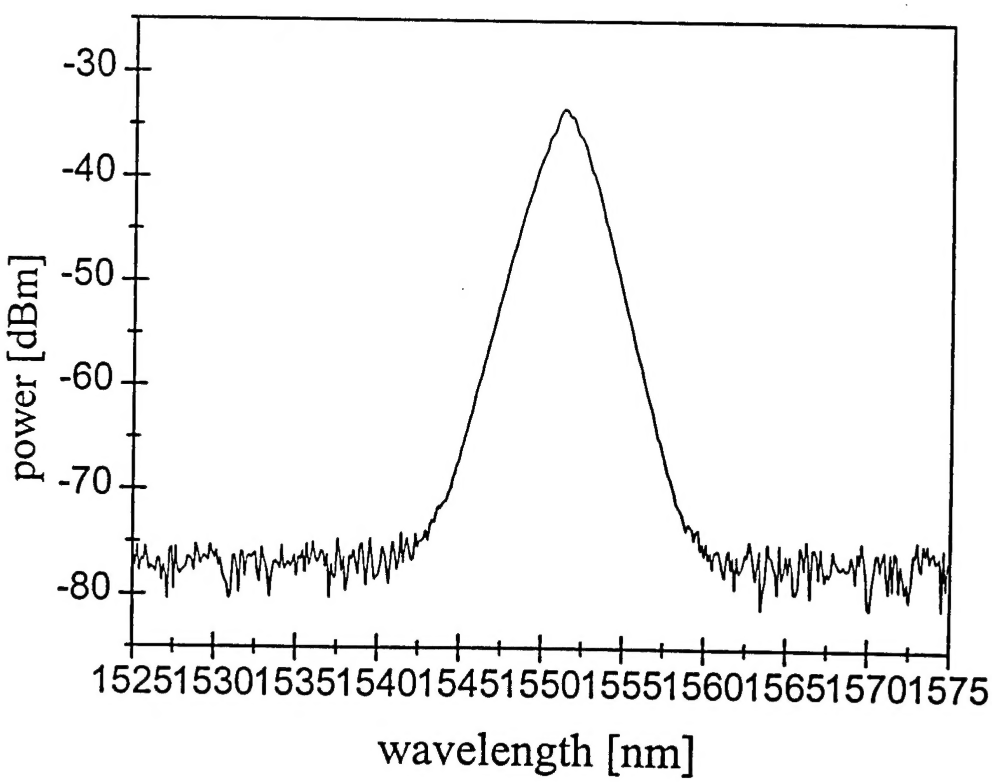
-90
power [dBm]
750 800 850 900 950 1000 1050 1100 1150 1200 1250
frequency [MHz]


(a)



-30
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power [dBm]
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wavelength [nm]


(b)

Figure 3

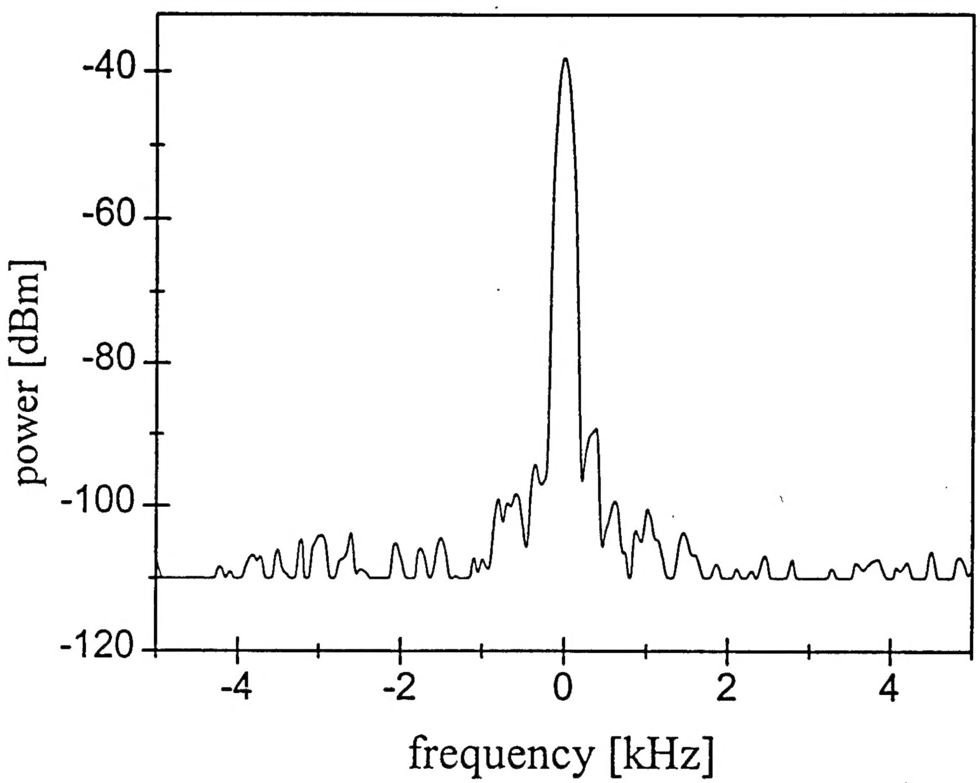


Figure 4

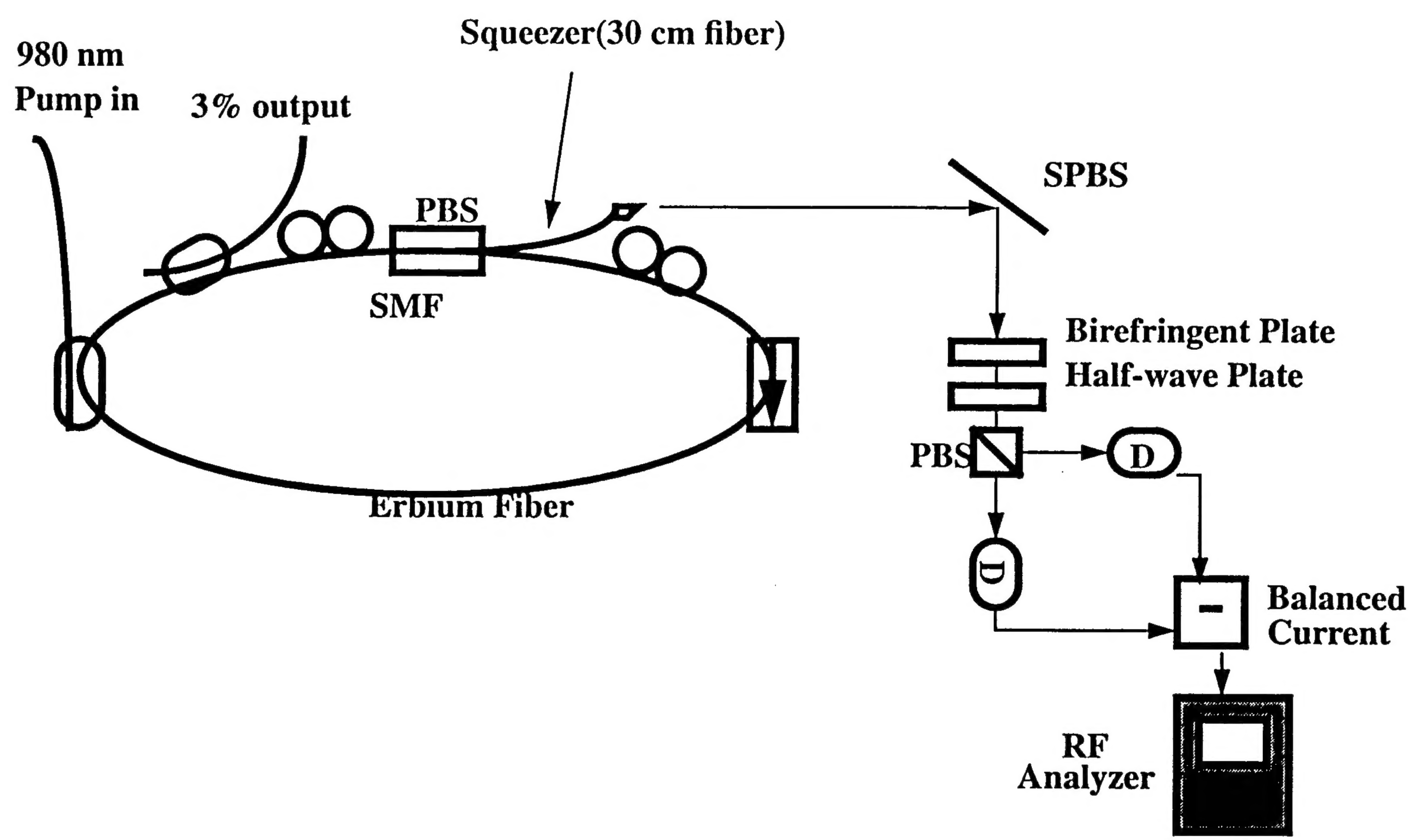
980 nm
Pump in
3% output
Squeezer(30 cm fiber)
PBS
SMF
Erbium Fiber
SPBS
Birefringent Plate
Half-wave Plate
PBS
D
D
Balanced
Current
RF
Analyzer

Figure 5

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